

Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal



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ARTICLE INFO

Article history:

Received 28 September 2014

Received in revised form 10 May 2015

Accepted 8 June 2015

Available online 2 September 2015

Keywords:

Koshi Basin
SWAT modeling
Climate change
Design standard
Design values
Uncertainties

ABSTRACT

Study region: The middle hilly region of the Koshi River Basin in Nepal.

Study focus: Assessment is made of the hydrological regime of the basin under climate change. Results from two Regional Climate Models (PRECIS-HADCM3Q0 and PRECIS-ECHAM05), based on IPCC-SRES A1B scenario, were bias corrected against historical gauged data. Hydrological impact simulations were conducted using SWAT model. Design flood estimation was done after extreme value analysis based on annual flow maxima.

New hydrological insights for the region: The study found that climate change does not pose major threat on average water availability. However, temporal flow variations are expected to increase in the future. The magnitude of projected flow for given return periods, however, strongly depends on the climate model run considered. The ECHAM05 results show higher flow changes than those estimated from the HADCM3 outputs. A relation was derived to estimate projected flood flow as a function of return period and flow estimated from historical series. Amidst the uncertainties, these predictions provide reasonable insight for re-consideration of design standards or design values of hydraulic structures under climate change.

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1. Introduction

The Koshi River is a trans-boundary river originating in China and passes through Nepal and finally meets the Ganga-River in India. The total catchment area of the river at its confluence with Ganga is 74,030 km² (FMIS, 2012). About 43% of this total area lies in China, 42% in Nepal and the remaining 15% in India (Sharma, 1997; FMIS, 2012). The Koshi River drains most of the eastern part of Nepal.

Livelihood of hundreds of millions of people of Nepal and India is dependent on the water availability in the Koshi River and, at the same time, frequent floods and drought have rendered millions vulnerable to their impacts (Chen et al., 2013). With the changing development trajectories of these countries, rapid development that includes urbanization, construction of roads and buildings, industrial development have taken place in recent years in the lower part of the basin. These activities are going to continue in the future as well. As in other parts of the world, long term water resources management is, thus, becoming a key driver for sustainable development of this region to meet the growing water demand for domestic, irrigation, fisheries and industrial uses, and mitigating the distressing impact of the water induced disasters, mainly floods.

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The world climate is changing more rapidly in recent years (Vijaya et al., 2011). Based on GCMs and RCMs, ISET-N (2009) reported that the mean annual temperature of Nepal is expected to increase by 1.4 °C by 2030, 2.8 °C by 2060, and 4.7 °C by 2090. The average annual mean of maximum temperature was predicted to increase by 2.1 °C under A2 scenario and by 1.5 °C under B2 scenario in 2080s in the Bagmati River Basin (Babel et al., 2014) while Bharati et al. (2012) projected that it will increase by 0.86 °C under A2 and by 0.79 °C under B1 scenarios in 2030s for the Koshi Basin compared to baseline 1976–2005. Increased temperature leads to greater evaporation and thus surface drying which thereby increases the intensity and duration of drought. However, the water holding capacity of air increases by about 7% per 1 °C warming which leads to increased water vapor in the atmosphere (Trenberth, 2011; Agarwal et al., 2014). It consequently, produces more frequent and intense precipitation events (Gurung and Bhandari, 2009). Agarwal et al. (2014), in their study of future precipitation in Koshi River Basin of Nepal, stated that projected precipitation under A1B scenario for the future periods (2020s, 2055s and 2090s) is expected to increase. Frequent and intense extreme climate and weather events will lead to increasing climatic variability that significantly increases the intra-annual variability of stream flow (Agrawala et al., 2003; Chaulagain, 2006). Climate change is, therefore, making water resources management further challenging adding additional uncertainty on the hydrological conditions. Assessment of the long term river hydrology with climate change impact on it has become imperative in recent years for long term sustainable water resources management (APN, 2008; Gosain et al., 2006; Chiew et al., 2011; Obeysekera et al., 2010; Shivakumar, 2010 and WECS, 2011) because it helps to build resilience to the possible impact of climate change through enhanced institutional flexibility and consideration of climate related risks in the planning process (Sharma and Shaky, 2005).

Developing countries are more vulnerable to extreme weather events under present day climatic variability which causes substantial economic damage (Monirul and Mirza, 2003). For the past thirty years, the number of flood disasters has increased compared to other forms of disasters in South Asia (Dutta and Herath, 2005) taking a heavy toll on properties and lives and caused more economic losses including infrastructure such as drinking water as well as water treatment plant, agricultural area degradation than any other hazards in Nepal (MoF, 2011). The recurrent devastating flood events in the Koshi River are quite enough to substantiate those observations and findings which have claimed huge damage in property, agriculture and loss of lives in the Terai plain of Nepal and Bihar of India at different time moments, e.g. 1869, 1870, 1954, 1968, 1971, 1980, 1984, 1991 (Mishra, 2008). The recent devastating one was the flood event of August 2008. This flood event caused the death of 4–6 persons, affected 6000 ha of agricultural land, damaging crops worth USD 3.7 million, displaced 40,378 people from 7102 families and damaged 4 km of the east–west highway in Nepal (ICIMOD, 2008). The devastation was much bigger in India. It claimed 42 lives (as of 25 August 2008), destroying 35,000 ha of crop, affected more than one million people with more than 70,000 being displaced (ICIMOD, 2008).

Due to the frequent flooding in Koshi River and its damages, there have been some efforts to control flood in both India and Nepal with the Koshi River Agreement in 1954. However, Koshi Flood in 2008 has alerted both countries regarding the functioning of the existing Koshi barrage and the river embankments. As a result, Koshi High Dam Project, which was envisioned in 1937 to effectively “cure” the flooding problem, has once again come forward as a revitalized issue for flood control, irrigation and hydropower generation. Koshi High Dam, the concrete dam of 269m height, is proposed to be constructed in Barahkshetra (near Chatara) with live storage of 4420 million cubic meters (mcm) and gross storage of 8500 mcm. The expected benefit from the dam is irrigation of 66,450 ha of land in Nepal and millions of hectares in India, flood control and 3489 MW of hydropower (DoED, 2013). As such, Nepal (the upper riparian), India (middle riparian), and even Bangladesh (lower riparian of the Ganga River Basin) have shown interest in the construction of the high dam. Recently, the sixth meeting of the India Nepal Joint Ministerial Commission on Water Resources (JCWR), held in November 2011 at New Delhi, agreed to expedite the completion of a Detailed Project Report for the Koshi High Dam Multipurpose Project. Similarly, the meeting of the JCWR held in January 2013 at Kathmandu decided to continue the feasibility study of the Dam (MoEn, 2014).

The beneficial aspects of the Koshi High Dam Project are very promising, but the project is not that simple as it seems. Apart from the existent socio-political issues, the proposed Koshi High Dam Project is going to face the challenges and uncertainties on its hydrological regime brought upon by the changing climate. Similarly, adequacy of the existing embankment to contain future floods, taking climate change into account, is yet to be assessed. The assumption of stationarity in traditional hydrologic considerations may no longer be valid under climate change (Milly et al., 2008) or indeed under natural variability (Frank and Kuczera, 2002) as cited in Chiew et al. (2011) while discussing on the implications of climate change for water resources management. Design of hydraulic structures such as the Koshi High Dam or embankments based on the analysis of historical hydrological data is, thus, simply not a good design considering the non-stationarity of the hydrological time series. Henngriff et al. (2006) reported in their study in the Baden-Wurtemberg area, that the ratio of design runoff under climate change and historical conditions ranged from 1.75 to 1.00. It was found to be decreasing with increasing return periods. For the 1000-year return period, the ratio was obtained to be 1.00, referring to the null effect of climate change. However, Das and Simonovic (2012) conducted a study to assess the impact of climate change to assess in the upper Thames River Basin of Canada using the results of fifteen different climate models for the future conditions in 2020, 2050 and 2080. They stated that the 100-year and 250-year flood magnitudes were found to be respectively 12% and 32% higher than for the baseline period (1979–2005) with negligible impact for the 10-year return period. It indicates that the magnitudes of flood flow increase under climate change impact, with higher changes for higher return periods.

It is thus prudent to predict the changes in the hydrological cycle including the extreme events under climate change scenario using appropriate hydrological models. Such models need to be robust enough to capture the hydrological phenomena with sufficient spatial detail. The results from such analysis will aid in making wise and rational decisions on the

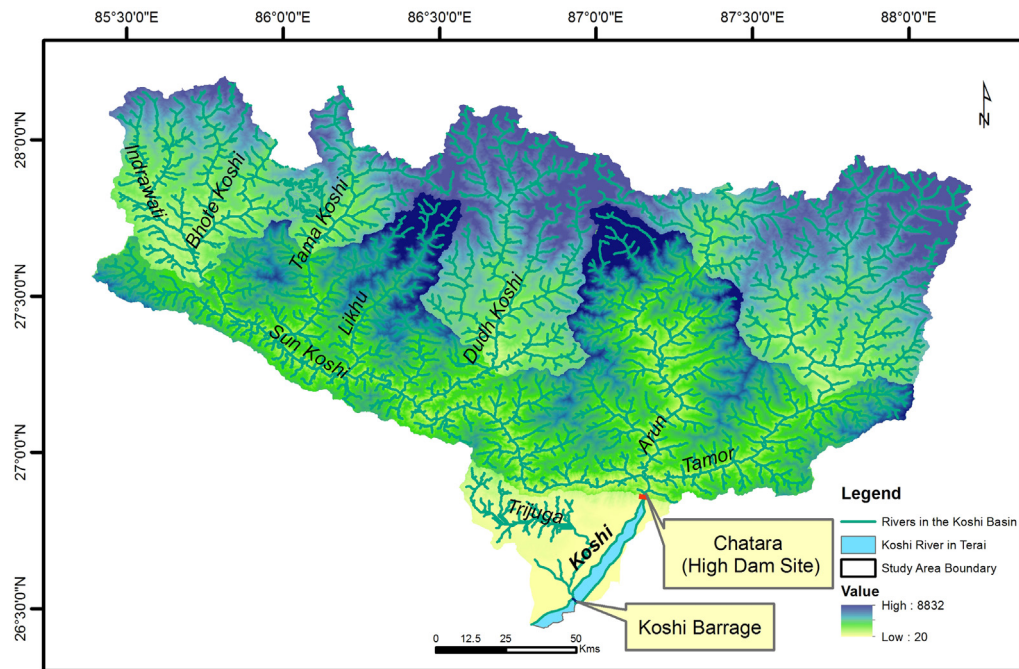


Fig. 1. Koshi River Basin in Nepal.

hard and soft approaches to face and overcome the challenges of the water resources management activities in the basin in the context of climate change.

This study assesses the changes in the hydrological regime of the Koshi River Basin with and without climate change using the Soil and Water Assessment Tool (SWAT model). This model has been widely used to assess the climate change impacts on the hydrological regime of various catchments across the world (Bharati et al., 2012; Gurung et al., 2013; Narsimlu et al., 2013; Lubini and Adamowski, 2013; Singkran et al., 2014; Bossa et al., 2014; Fontaine et al., 2002). Considering the projected data availability, for this purpose the results from two regional climate models based on the IPCC SRES greenhouse gas emission scenario A1B were used to assess the future climatic conditions (IPCC, 2007).

2. Study area: The Koshi River Basin

The Koshi River has three main tributaries viz. Tamor in the eastern part, Arun in the middle and Sunkoshi in the western part of the basin. The Sunkoshi River consists of 5 major tributaries: the Indrawati, the Bhothe-Koshi, the Tama Koshi, the Likhu and the Dudh Koshi (Fig. 1). The Sun-koshi, the Arun and the Tamor meet at Tribenighat, flow through Barakhshetra gorge for a length of about 15 kms and enters into the Terai Region (plains) of Nepal after Chatara.

The Koshi River Basin covers three major ecological zones of Nepal with a transverse length (north-south) of about 150 km. These zones are: (i) Snow covered Himalaya in the north, (ii) hilly region in the middle and (iii) plain region of Terai in the south. The variation of altitude in this short north-south reach is quite sharp ranging from 95 m to 8848 m. The High Himalayan region of the Koshi basin within Nepal is about 8220 km² (>3000 m) where glacial lakes are common. ICIMOD (2011) mapped 599 glacial lakes in the Koshi Basin covering an area of 26 km².

The upstream Himalaya part of the Koshi Basin covers an area of about 17,620 km², mainly covered with forests and agricultural land. This region is the high rainfall receiving zone of the basin. The downstream part in the Terai region of Nepal covers an area of 2000 km² before it enters into Indian Territory. The Terai region is highly populated. Agricultural land occupies the main part of this plain. This study focused on the middle, hilly part of the basin. Because this region is a high rainfall receiving zone, rainfall-runoff (hydrologic simulation) study needs to be carried out to assess the impact of the climate change on the hydrology. The SWAT model was employed to assess the impact on the basin hydrology, and the Snow Runoff Model (SRM) for quantifying the boundary flows from the Himalayan region. Given that snow and glacial hydrology are dominant in the Himalayan region, SRM modeling was performed to comprehend the snowmelt phenomenon dividing the Himalayan catchment into five sub-catchments; see Khadka et al. (2014) for details.

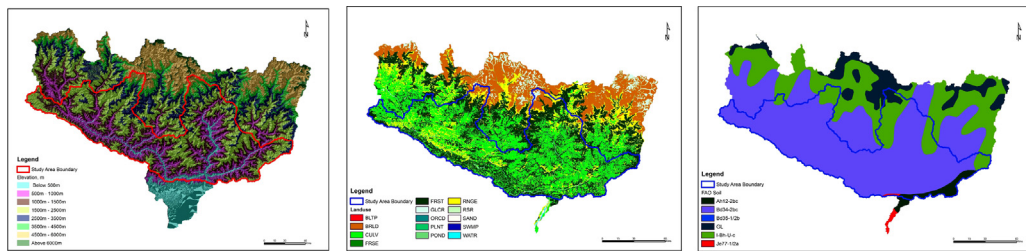


Fig. 2. Digital Elevation Model (DEM), landuse and soil maps of the Koshi River Basin.

3. Materials and methods

3.1. Hydrologic simulation

A semi-distributed, time continuous watershed model, Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; SWAT, 2005) was used for rainfall-runoff modeling in this study. Conceptually, SWAT divides a watershed into sub-watersheds. Each sub-watershed is connected through a stream channel and further discretized into Hydrologic Response Units (HRUs). A HRU is a unique combination of soil and vegetation type in a sub-watershed, and SWAT simulates the hydrological variables and runoff results at the HRU level and aggregates these results to the catchment scale by applying a weighted average to the HRU results. The runoff is routed to obtain the total runoff for the watershed at the outlet.

The SWAT model for Koshi Basin was set up with the Arc SWAT2009 interface (Neitsch et al., 2011). The data required for the model implementation and the steps involved are briefly discussed below. Coefficient of Determination (R^2) and Nash–Sutcliffe Simulation Efficiency (E_{NS}) were used as the goodness of fit measures during calibration and validation of the model.

3.2. Data used in simulation

3.2.1. Topographic, land use and soil data

Topographic, land use and soil map data are the spatial data required for hydrological simulations using the SWAT model. The topography of the basin is defined by the Aster GDEM v2.0¹ Digital Elevation Model (DEM) for the Koshi River Basin. It has a spatial resolution of 30 m. Fig. 2 shows this DEM.

Landuse data for the study area were obtained from the Department of Survey, Nepal (SD, 1996). Reclassification of the landuse map was done and the respective model parameters were selected from the SWAT database corresponding to the specific landuse/cover types. Fig. 2 shows the landuse map for the Koshi River Basin. The FAO soil map² was applied and the soil data properties obtained from the FAO soil properties database (FAO, 2002). Refer Fig. 2.

3.2.2. Historical time series data

Historical meteorological and hydrological data were collected from the Department of Hydrology and Meteorology (DHM), Government of Nepal (DHM, 2012). The meteorological data used for the SWAT modeling were daily precipitation, daily maximum and minimum temperature, daily relative humidity, wind speed and sunshine hours. Gauged flow data were used in the model for two purposes; first to define inlet discharge points for the basin to simulate the existing conditions and second for performing sensitivity analysis, calibration and validation of the model at the outlet. Since the SWAT model was used for the hilly part of the basin, inlet discharge points were defined in the model at five points (Fig. 3) to incorporate the flow generated from the mountainous/snow-covered part of the basin.

3.2.3. Projected future climate data

Simulation results for the region from two Regional Climate Models (RCMs), PRECIS-HADCM3Q0 and PRECIS-ECHAM05, were used in this study to generate the future flows. They both are based on the IPCC greenhouse gases emission scenario (SRES) A1B. Detailed discussion of these models is provided in ADPC et al. (2012). The RCM outputs were considered for the baseline period 1976–2000 and for the future period 2040–2060. The two RCM models are hereafter denoted as ECHAM05 and HADCM3. Spatial resolution of the data is 25 km. Bias correction of the climate data (rainfall and mean, maximum and minimum temperature) was done against gauged historical data. Recently, several studies focused on methods for bias correction of climate model outputs prior to use in hydrological impact studies. In comparison with the basic method of bias correcting the mean, more advanced methods are recommended bias correcting both the mean and the variance, and – for rainfall – bias correcting a range of quantile values versus probability (Sunyer et al., 2014). Methods have been

¹ AsterGDEMv2.0 is a property of METI and NASA.

² http://www.tucson.ars.ag.gov/agwa/index.php?option=com_jdownloads&Itemid=&view=viewdownload&catid=17&cid=113.

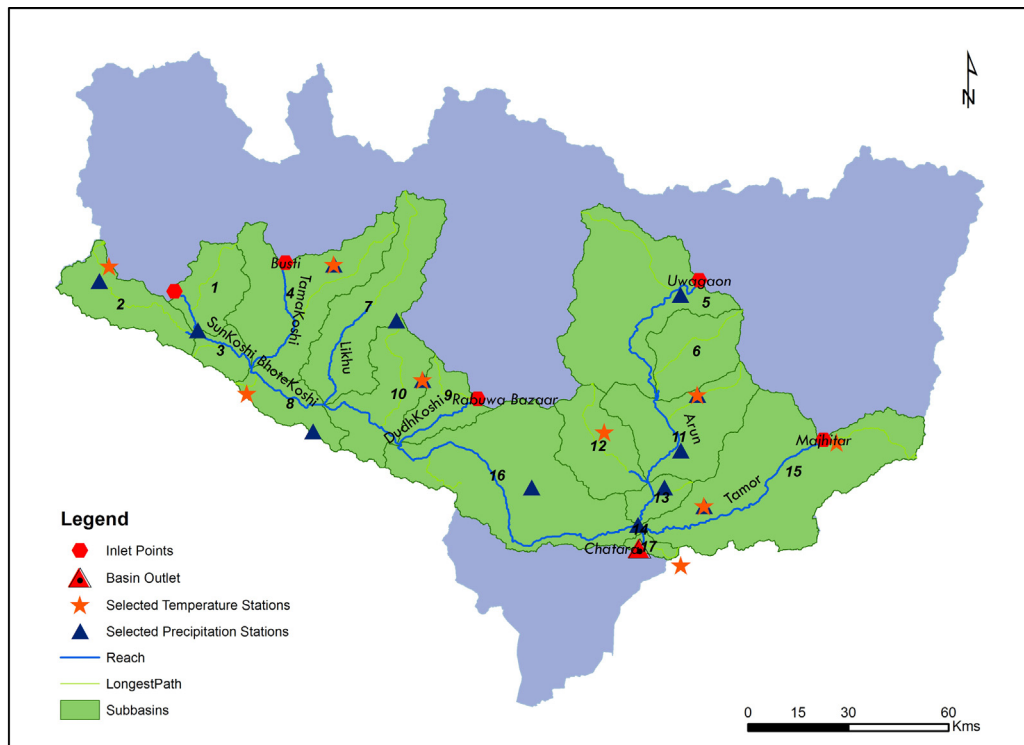


Fig. 3. Delineation of the catchment area.

developed to conduct this quantile based bias correction in a non-parametric (Gudmundsson et al., 2012; Ntegeka et al., 2014) or parametric way (Rana et al., 2014; Terink et al., 2010; Leander and Buishand, 2007). In order to capture the day-to-day climatic variability, the parametric Power Transform method for precipitation and the mean and standard deviation adjustment for temperature were opted in this study following their impressive performance in the Meuse river basin (Leander and Buishand, 2007) and the Rhine river basin (Terink et al., 2010). Further, Mean Bias Error (MBE) and Root Mean Square Error (RMSE) of uncorrected and bias corrected versus observed values were considered for spatial evaluation of bias correction, as opted by Terink et al. (2010). For temporal bias, coefficient of determination (R^2) has been considered to evaluate the performance of the bias correction. Monthly precipitation values for 1976–2000 in each region were considered for evaluating the statistics. Significant improvement on R^2 values for both hilly and mountain regions have been obtained between observed and bias corrected precipitation data [$R^2 = 0.26$ to 0.61 for HADCM3 and 0.34 to 0.62 for ECHAM for SWAT domain; similarly $R^2 = 0.38$ to 0.73 for HADCM3 and 0.36 to 0.72 for ECHAM for SRM domain]. MBE and RMSE were also improved significantly for both models and regions.

3.3. Flow simulation

3.3.1. Model setup

To account for the flow contribution from the mountainous part of the basin, the region was divided into five sub-basins. Outlets of these sub-basins were defined in SWAT as inlet points, viz. Majhitar for Tamor sub-basin, Uwagaon for Arun sub-basin, Rabuwa Bazar for Dudh Koshi sub-basin, Busti for Tama Koshi sub-basin and Pachuwarghat for both Indrawati and Sunkoshi-Bhotekoshi sub-basin. It is noted here that the Likhu river sub-basin has an insignificant snow covered area and thus was included in the SWAT domain. The sub basins with the river reaches, inlet and outlet points are shown in Fig. 3.

Five slope classes (0–5%, 5–10%, 10–20%, 20–50% and >50%) were applied and the slope grids were reclassified based on the DEM. These were combined with the landuse and soil data to define the HRUs to each sub-basin.

Daily data from 16 rainfall stations, 12 temperature stations and 3 synoptic stations (daily wind speed, relative humidity and solar radiation data) were used for the period of 1976–2008 (Fig. 3). Missing temperature data for various stations were filled using an elevation correction approach with the data from a reference station and monthly lapse rate calculated comparing with the reference stations.

Table 1
Calibrated parameters and the values.

| Parameters | Description | Bound | | Calibration results | |
|-------------|--|-------|-------|---|----------|
| | | Lower | Upper | Fitting value | Method |
| CN2.mgt | Initial SCS CNII value | –25 | 25 | 1.05 (Forest, Cultivated, Rangeland, Barren Land) | Multiply |
| Sol.Awc.sol | Available water capacity (mmH ₂ O/mm soil) | –25 | 25 | 0.75 | Multiply |
| Canmx.hru | Maximum Canopy Storage, (mm H ₂ O) | 0 | 10 | 2.5 (Forest), 1 (Cultivation) | Replace |
| Gw Delay.gw | Groundwater Delay (days) | 0 | 500 | 8 | Replace |
| Ch_K2.rte | Hydraulic conductivity in main channel, mm/hr | 0 | 150 | 55 | Replace |
| CH.N.rte | Manning's Roughness in main canal | 0 | 1 | 0.035 | Replace |
| SURLAG.bsn | Surface runoff lag time (days) | 1 | 24 | 1 | Replace |
| SFTMP.bsn | Snowfall temperature, °C | –5 | 5 | 1.5 | Replace |
| SMTMP.bsn | Snowmelt base temperature, °C | –5 | 5 | 3 | Replace |
| SMFMX.bsn | Melt factor for snow on June 21 (mm H ₂ O/°C/day) | 0 | 10 | 5.6 | Replace |
| SMFMN.bsn | Melt factor for snow on December 21 (mm H ₂ O/°C/day) | 0 | 10 | 1.5 | Replace |
| TIMP.bsn | Snowpack temperature lag factor | 0 | 1 | 0.51 | Replace |

3.3.2. Sensitivity analysis

Sensitivity analysis was carried out in order to evaluate the response of model output with reference to change in various flow related parameters. A Latin Hypercube Sampling and One-at-a-time sensitivity analysis (LH-OAT) method was applied using the observed flow. Top ten sensitive parameters affecting flow were then further used in calibrating the model.

4. Results and discussion

4.1. Flow characteristics

Flow in the Koshi River is the combination of snow melt runoff and rainfall. The observed daily flow data (from 1977 to 2008) at the outlet station Chatara (catchment area of 54,100 km²; DHM, 2008) showed that it carries a flow of 1500 m³ s^{–1} on average. However, the inter-annual variation is quite high, ranging from 618 m³/s to 2055 m³/s. The monthly minimum and maximum flows for this period were 231 and 6180 m³/s respectively. The daily minimum and maximum flow values recorded during this period are respectively 201 and 11,900 m³/s, with the coefficient of variation greater than one. It shows that daily fluctuation of flow in the dry season is quite low while it is very high during monsoon season as depicted in Fig. 8. It is because the monsoon flow is mainly governed by rainfall which is a common characteristic in all rivers of Nepal (Sharma, 1997; Thapa and Pradhan, 1995). An instantaneous maximum flow of 24,000 m³/s was recorded in 1980. The instantaneous flow for this period is, thus, more than double of the daily maximum. After comparison of the simulated flows for the historical period with the observed daily flows, the average of the simulated daily flow was found only 2% lower than the average observed flow. However, the daily minimum and maximum simulated flows were respectively 14% higher and 19% lower than those of the observed flow. This implies that there is a slight overestimation of low flows and underestimation of the high flows by the model.

4.2. Model results

4.2.1. Model calibration

The observed flow time series at the outlet station, Chatara, was divided into three distinct periods, the 'warming-up', 'calibration' and 'validation' periods, i.e. from 1986–1990, 1991–2000 and 2001–2006, respectively. Table 1 below shows the parameters used for the calibration with the final calibrated values.

Observed versus simulated hydrographs are shown in Fig. 4. In Fig. 5 cumulative volume of flows for the simulation period is shown. From these graphs it can be clearly seen that the model simulates the flow very well and the hydrographs are in good agreement with the rainfall pattern. The high values of the Nash–Sutcliffe efficiency ($E_{NS} = 0.97$) and the coefficient of determination ($R^2 = 0.98$) and the small volume difference between the observed and simulated values of 0.21%, show a very strong predictive capability of the model.

4.2.2. Validation

Figs. 6 and 7 show the comparison between observed and simulated flows for the validation period. Both graphs show that the simulated values are again in good agreement with the observed values. This is justified by the high E_{NS} of 0.87 and R^2 of 0.88, and the small volume difference of 6.5%. However, for the year 2003, the model underestimates the flow. This underestimation may be due to erroneous data in the observed flow values.

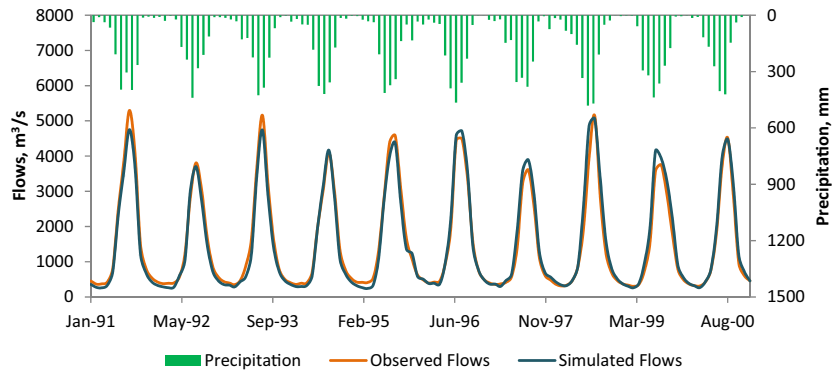


Fig. 4. Observed vs. simulated hydrographs for calibration period.

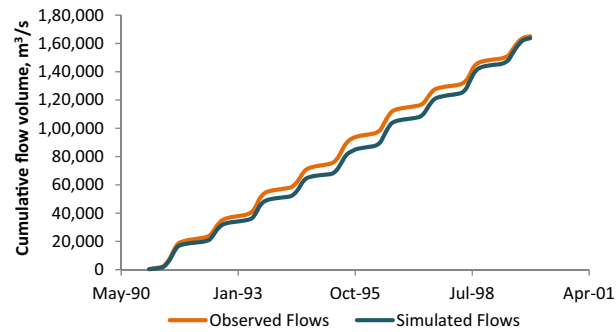


Fig. 5. Comparison of observed vs. simulated water volumes for calibration period.

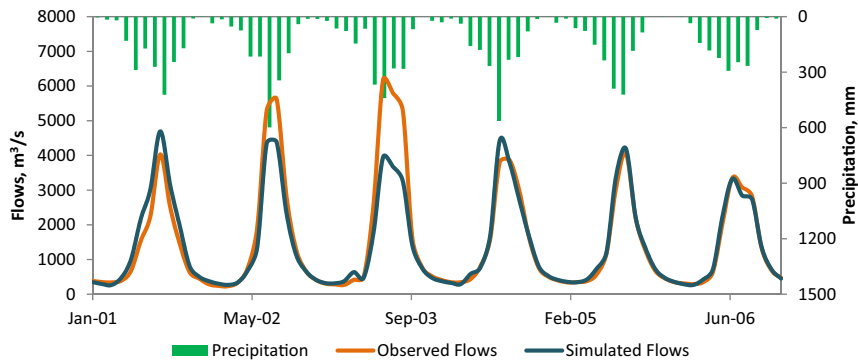


Fig. 6. Observed vs. simulated hydrographs for validation period.

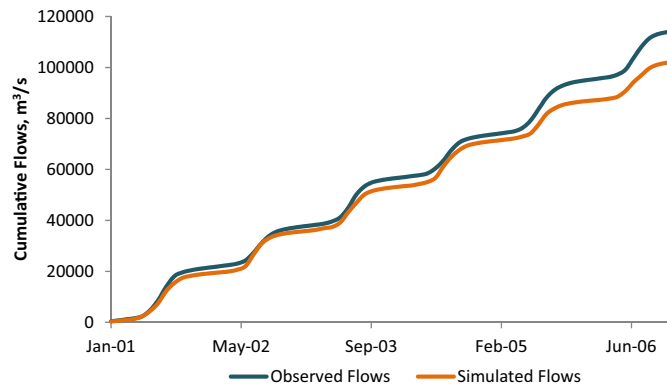


Fig. 7. Comparison of observed vs. simulated volumes for validation period.

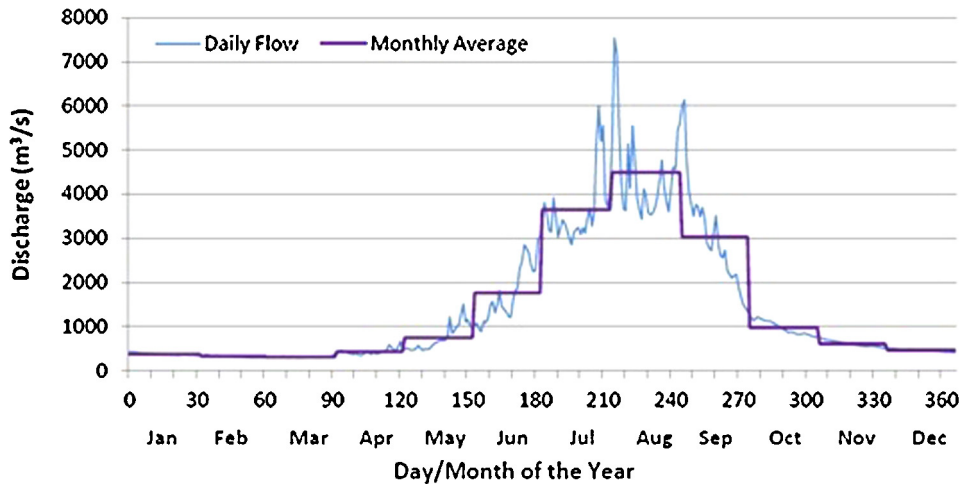


Fig. 8. Daily and monthly averaged flows at Chatara (DHM, 2008).

4.2.3. Future flow simulation

After simulation of the bias corrected ECHAM05 and HADCM3 daily results in the SWAT model, the climate change impacts on design floods were assessed.

These design values are of importance while constructing hydraulic structures like dams, embankments or bridges over rivers. They were derived from the annual maximum values based on the following steps:

- Frequency analysis of annual instantaneous maximum flow recorded at the gauging station (Chatara) for different return periods ($Q_{T,i}$), where a Log-Pearson III distribution was calibrated to the observed flow.
- Similarly, frequency analysis of annual maximum daily flows of the historic data for different return periods ($Q_{T,d}$).
- A ratio was then obtained by dividing the maximum instantaneous and daily flows for each return period T , i.e.

$$R_T = \frac{Q_{T,i}}{Q_{T,d}} \quad (1)$$

- Frequency analysis of annual maximum daily flows of the projected period for different return periods ($Q'_{T,d}$).
- Calculation of instantaneous maximum flows ($Q'_{T,i}$), also called design floods, by multiplying the maximum daily flows derived from the projected series for different return periods with ratio obtained from step (iv) for the respective return periods, i.e.

$$Q'_{T,i} = Q'_{T,d} \times R_T \quad (2)$$

4.3. Comparison of flow statistics of historical and projected flow series

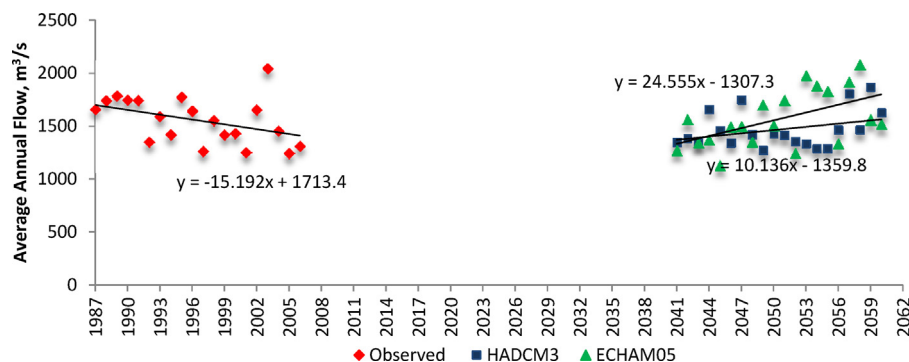
To consider a 20-year period for both the historical and future series, the historical (observed) flows were limited to the period 1987–2006. The period 2040–2060 was considered for the future (RCM based) flows. The 20-years period was further divided into 2 parts of 10 years each to assess the changes within the periods. Note that model based future flows were compared with the historical observed data in this study. The flow statistics of historical and projected flow series are presented in Table 2. The data show that the estimated average future flow is slightly less than the baseline flow of 1987–1996, except for the ECHAM05 results and the 2050s. From the water availability point of view, climate change is not going to impact greatly the basin water resources. However, both daily and monthly variations in flow are quite high. It demands for strong regulation of storage facilities such as the Koshi High Dam, in order to fulfill the downstream water requirements for irrigation, domestic and industrial uses, to generate stipulated hydropower and for flood control. Quite low value of the safe yield (i.e. Q_{95} : probability of exceeding the given flow by 95% of the time) and very high values of flood flows (Q_1 and $Q_{0.1}$) justifies the need of such water storage.

4.3.1. Change in annual flow

Comparison of the annual average flows between the historical data and future flows, show a slightly decreasing trend of about $15 \text{ m}^3/\text{s}$ per year (Fig. 9). Sharma et al. (2000) also found decreasing flow trends for the Koshi River when analyzing the flow data of 1974–1994. Similar observations were made for other major Nepalese rivers such as Narayani, Karnali, Kaligandaki (WECS, 2011). However, the increasing trend on the annual average flow of $17 \text{ m}^3/\text{s}$ ($25 \text{ m}^3/\text{s}$ by ECHAM05 and $10 \text{ m}^3/\text{s}$ by HADCM3) is clearly seen in both projected cases (ECHAM05 and HADCM3).

Table 2Comparison of flow statistics of historical and projected flow series, Unit: m³/s.

| Variables | Observed | | Projected ECHAM05 | | Projected HADCM3 | |
|--------------------------------|----------------------|-----------|-------------------|-----------|------------------|-----------|
| | 1987–1996 (baseline) | 1997–2006 | 2041–2050 | 2051–2060 | 2041–2050 | 2051–2060 |
| Q_{avg} | 1654 | 1471 | 1429 | 1717 | 1448 | 1500 |
| CV | 0.97 | 1.07 | 1.15 | 1.29 | 1.17 | 1.2 |
| $Q_{avg} + Sdv (\mu + \sigma)$ | 3257 | | | | | |
| Min daily | 255 | 201 | 219 | 247 | 230 | 245 |
| Max daily | 9610 | 9480 | 23,780 | 36,020 | 15,000 | 19,830 |
| Min monthly | 299 | 231 | 257 | 256 | 237 | 261 |
| Max monthly | 6089 | 6181 | 5620 | 8614 | 4673 | 6844 |
| Annual min | 1354 | 1251 | 1135 | 1247 | 1280 | 1296 |
| Annual max | 1795 | 2055 | 1713 | 2088 | 1757 | 1881 |
| Q_{90} | 378 | 315 | 289 | 290 | 272 | 284 |
| Q_{95} | 350 | 294 | 275 | 268 | 256 | 265 |
| Q_1 | 6230 | 6470 | 7625 | 9752 | 8443 | 8148 |
| $Q_{0.1}$ | 7730 | 8300 | 14,530 | 26,450 | 12,700 | 15,760 |

**Fig. 9.** Future changes in annual flows.**Table 3**

Future change in monthly flows.

| Months | Observed | | ECHAM05 | | HADCM3 | |
|--------|------------------------------------|-----------|-----------|-----------|-----------|-----------|
| | 1987–1996 | 1997–2006 | 2041–2050 | 2051–2060 | 2041–2050 | 2051–2060 |
| | (Baseline flow, m ³ /s) | (%) | (%) | (%) | (%) | (%) |
| Jan | 442 | –18 | –17 | –10 | –21 | –9 |
| Feb | 379 | –16 | –18 | –14 | –13 | –16 |
| Mar | 390 | –19 | –23 | –11 | –23 | –27 |
| Apr | 455 | –12 | –23 | –26 | –34 | –11 |
| May | 876 | –22 | –22 | –13 | –31 | –23 |
| Jun | 2024 | –13 | 19 | 19 | 5 | 10 |
| Jul | 3928 | –2 | –7 | 26 | –7 | –8 |
| Aug | 4740 | –8 | –26 | –14 | –23 | –13 |
| Sep | 3420 | –13 | –14 | 4 | –15 | –16 |
| Oct | 1644 | –16 | –18 | 14 | 8 | 3 |
| Nov | 874 | –21 | –19 | 6 | –8 | –9 |
| Dec | 572 | –17 | –13 | –1 | –13 | –13 |

4.3.2. Change in monthly flow

Development of water storage systems can be the strategies for climate change adaptation (ICIMOD, 2009). However, possible water withdrawals from the river under no storage condition or the storage reservoir capacity and/or operation of the reservoir depend on the monthly availability of the flow and its variation. To evaluate this aspect of flow, the percentage change in the decadal average of monthly flows for the projected periods versus the baseline average monthly values were calculated and are depicted in Table 3. The changes in monthly flows vary from decreases with 30% to increases by more than 27%. Most of the flow is decreasing during the lean period and increasing in June and July, which are in the period of high flows. This means that unfavorable water withdrawal conditions are more likely in the future. It demands higher volumes of water to be stored to meet the dry season water demand if water storage projects such as the Koshi High Dam are constructed. Changes in the operation rules moreover become a necessity to deal with these changes in monthly flows ultimately.

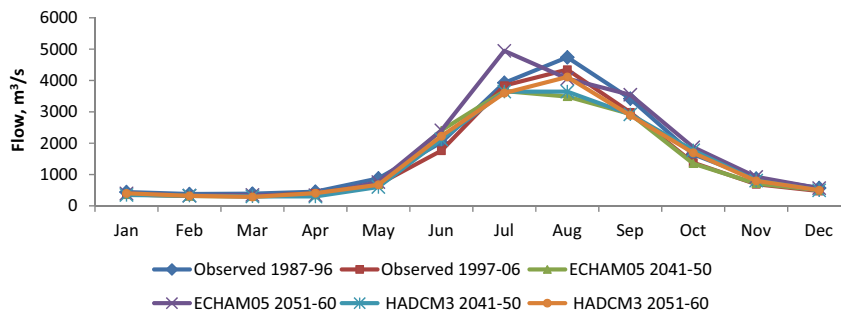


Fig. 10. Monthly averaged flows for historical and future conditions.

Table 4

Frequency of highest monthly flows.

| Period | | June | July | August | September |
|----------|-----------|------|------|--------|-----------|
| Observed | 1987–1996 | 0 | 0 | 10 | 0 |
| | 1997–2006 | 0 | 2 | 8 | 0 |
| ECHAM05 | 2041–2050 | 4 | 2 | 1 | 3 |
| | 2051–2060 | 3 | 4 | 0 | 3 |
| HADCM3 | 2041–2050 | 3 | 0 | 5 | 2 |
| | 2051–2060 | 2 | 2 | 3 | 3 |

4.3.3. Early shifting of peak flow

Changes in the timing of water flows or water availability in the river are of special importance for the water management. Temporal shifting of monthly peak flows from July to August was observed in the Bagmati River Basin by Sharma and Shakya (2005), while Shrestha (2004) found early shifting of peak flows along the Kaligandaki River in western Nepal. To assess if there is any shift in timing of river flows, 10 year average monthly flow hydrographs for the historical and future periods are plotted in Fig. 10. The figure suggests a clear shift of peak monthly flows from August under existing conditions (baseline) to July for future projected conditions (ECHAM05). However, the shift in peak monthly flows is not distinct for the HADCM3 model. As an attempt to get more clarity, frequencies of highest monthly flows are presented in Table 4. The table vividly shows that the maximum monthly flows in the Koshi River have been taking place in August for the baseline period. For the future scenarios, the number of cases of maximum flows occurring in June and July show that early shifting of the hydrograph peaks is likely.

4.3.4. Flows with different exceedance probabilities

Important values of flow duration curves, i.e., flows with 0.1%, 1%, 90% and 95% probability of exceedance for both observed and projected flows are listed in Table 2 for different decades. The table shows a significant increase in flows for 1% and 0.1% exceedance probabilities for the 2050s. They are as high as 57% (ECHAM05) and 31% (HADCM3) for the 1% exceedance flow and as high as three and half times (ECHAM05) and two times (HADCM3) for the 0.1% exceedence flow. However the 90% and 95% exceedance flows are decreasing by 25% as compared with the historical case for the same period. This result indicates a higher probability for extreme flows to increase and low flows, hence water availability, to decrease during the lean seasons in the future.

4.3.5. Flood frequencies and volumes

Frequency and volumes of peak flows and floods are essential information for the design of a dam with the objective of flood control. Before we can analyze such flood frequencies and volumes, we first need to define floods. A flood is in this study considered as any daily flow event for which the peak flow is higher than the long term mean daily flow plus one times the standard deviation ($\mu + \sigma$) based on the baseline period (1987–1996). This flow equals 3257 m³/s (Table 2). This definition is employed in previous studies by Sharma and Shakya (2005) and WECS (2011). Calculated number of flood days, maximum number of consecutive flood days and corresponding flood volumes are for both the historical and future periods given in Table 5. It shows that the number of consecutive flood days is decreasing in the future. This obviously is due to the more intense rainfall. However, the number of such rainy days producing floods will be less. It moreover is noted that the number of consecutive flood days and the flood volumes is higher in the 2050s than in the 2040s. When the average of the flood volumes obtained from the ECHAM05 and HADCM3 results is considered to compute the future flood volume to be kept in the flood storage zone of the reservoir, an average maximum flood volume of about 2400 million cubic meter is obtained. The flood storage zone to be kept in the reservoir to accommodate such future flood should be three times more than the flood zone capacity estimated from the baseline data.

Table 5

Flood information of historical and projected scenarios.

| Flood Volumes | Observed 1987–1996 | 1997–2006 | Projected ECHAM05 2041–2050 | 2051–2060 | Projected HADCM3 2041–2050 | 2051–2060 |
|--|-----------------------|-----------|--------------------------------|-----------|-------------------------------|-----------|
| No. of days Exceeding ($\mu + \sigma$), 3257 m ³ /s | 685 | 567 | 415 | 604 | 435 | 488 |
| Maximum No. of consecutive days exceeding ($\mu + \sigma$), 3257 m ³ /s | 71 | 104 | 34 | 69 | 26 | 48 |
| Maximum Volume (in 10 ⁶ m ³) | 830 | 819 | 2055 | 3112 | 1296 | 1713 |

Table 6

Return period of flows for historical and projected conditions.

| Return period (year) | Flow (m ³ /s) Historical | ECHAM05 | HADCM3 | Projected average |
|----------------------|--|---------|---------|-------------------|
| 2 | 7246 | 11,878 | 11,207 | 11,543 |
| 5 | 9464 | 19,184 | 16,601 | 17,893 |
| 10 | 11,579 | 26,349 | 21,388 | 23,869 |
| 20 | 14,197 | 35,617 | 27,147 | 31,382 |
| 50 | 18,666 | 52,381 | 36,773 | 44,577 |
| 100 | 23,041 | 69,758 | 46,042 | 57,900 |
| 500 | 38,034 | 134,648 | 77,088 | 105,868 |
| 1000 | 47,445 | 178,539 | 96,165 | 137,352 |
| 10,000 | 101,080 | 457,143 | 201,103 | 329,123 |

4.4. Impacts of climate change on design floods

The impacts of climate change on water resources development works does not only depend on changes in the flood volumes but also on timing and magnitude of the peak flows. The magnitude of the floods is particularly important when we deal with hydraulic structures like the spillway of the dam to dispose the flood water and the embankments to contain the flood water within the river bed. Timing and duration of peak flows dictate the operation rules of the reservoir both for water use and safe disposal of flood water. Therefore, design floods were estimated for various return periods with and without climate change scenarios.

The estimated instantaneous floods for various return periods are for historical as well as future conditions given in Table 6. Average values of the ECHAM05 and HADCM3 based floods were calculated. The following conclusions can be drawn from the results in Table 6.

1. For a given return period, the magnitudes of the future design flows are for both models higher than that of the historical ones. This shows higher future design flows. It demands higher capacity of the flow disposing structures such as the dam spillway and of the river embankments.
2. The higher flood values point out the insufficiency to assume that the design flood values are stationary over time. In other words, design standard should be revisited to consider the climate change in hydraulic infrastructure design, i.e. higher flood flows of lower return periods should be considered than what we are using now. For example, to design a hydraulic structure for a return period of 100 years (peak flow of 57,900 m³/s, Table 6), the results after the future projections show that we need to increase the design return period to more than 1000 years when historical design floods keep being applied (47,445 m³/s, Table 6). It can be observed from the table that the 10,000-year flood will become a 500-year flood under the future conditions considered in this study. These results suggest extreme increases in the instantaneous river flows.
3. The changes in design floods are different when they are based on one versus the other RCM. The design floods estimated from the ECHAM05 results are higher than those estimated from the HADCM3 model. It shows the existence of uncertainties in future estimations. This uncertainty should be taken into account when designing hydraulic structures. For example, for the 100-year return period flood, the ECHAM05 estimate is almost 50% higher than the HADCM3 estimate.
4. The ratio of future flow over the historical one is higher for higher return periods. In other words, if we want to adjust the design floods to accommodate to climate change, the adjustment depends on the return period considered.

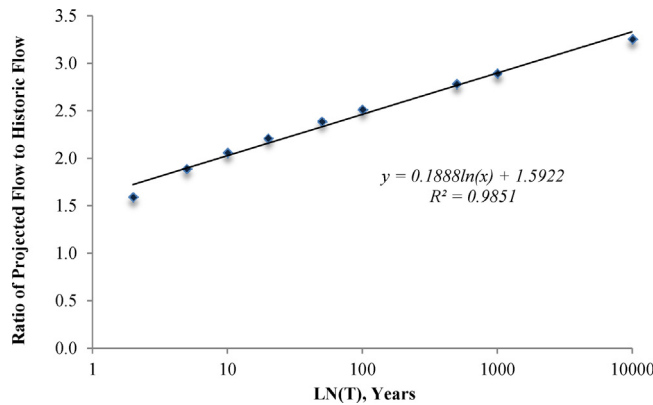


Fig. 11. Ratio of future over historical instantaneous peak flows versus return period T .

To simplify the analysis, an attempt was made to develop a relationship by calibrating the ratio of the future over historical peak flows versus the corresponding return periods (Fig. 11). The following relation was obtained:

$$\frac{Q_p}{Q_h} = 1.592 + 0.188 \ln(T) \quad (3)$$

where Q_p is the future peak flow, Q_h the historical peak flow and T the return period (years).

The future design flood for a given return period can, thus, be estimated based on that relationship as follows:

$$Q_p = [1.592 + 0.188 \ln(T)]Q_h \quad (4)$$

5. Conclusion

This study assessed the expected climate change impact on river hydrology of the Koshi River and its implication on the proposed Koshi High Dam Project. Two Regional Climate Model future projection runs viz. PRECIS-HADCM3Q0 and PRECIS-ECHAM05 were acquired and used for this purpose. Both model runs are based on the IPCC SRES A1B scenario. The run results for daily rainfall, and maximum and minimum temperatures were bias corrected against observed historical data using the power transformation method for rainfall and the mean and standard deviation adjustment method for temperature. The objective functions used while performing bias correction were the Mean Bias Error (MBE) and Root Mean Square Error (RMSE) for the spatial variations and the coefficient of determination (R^2) for the temporal bias. Satisfactory improvement on MBE, RMSE and R^2 values have been obtained between observed and bias corrected data.

Bias corrected rainfall and temperature data were used in the calibrated and validated SWAT model to assess the future hydrological regime of the basin. The study found that climate change is less likely to pose the threat on average water availability in the Koshi River Basin. However, temporal variation in river flows is expected to increase in the future. Most of the flow is decreasing during the lean season and increasing during the high flow season. The future RCM based projections show a decrease in the long term monthly flow by more than 30% in the drier months and an increase by more than 25% in the high flow months when compared to the baseline values. The results suggest a shift of the peak monthly flow from August under baseline conditions to July under ECHAM05 based projected future conditions. However, the shift in peak monthly flow is not obvious for HADCM3. The peak flows for 0.1% exceedance probability are as high as three and half times the corresponding baseline value for ECHAM05 and two times for HADCM3.

Design flood estimation method was proposed to estimate the peak and flood flows for different return periods. The method is based on extreme value analysis of the daily maximum flows. The magnitudes of the design flood values were found to be higher than those based on the historical series. The flood magnitudes obtained from the ECHAM05 results are, however, higher than those estimated from the HADCM3 results. A relation was derived to estimate future design flood flows as a function of return period and corresponding historical design flood flow.

It was concluded that any design based on a 100-year design flood flow ($57,900 \text{ m}^3/\text{s}$) may need to be changed to a design flood flow for a return period of more than 1000 years, when based on historical data ($47,445 \text{ m}^3/\text{s}$), in order to account for the impact of climate change. The results in this study furthermore show that the 10,000-year return flood may occur on average every 500 years in the future. Amidst the uncertainties, these projections provide reasonable insight in support of alterations or re-consideration of design standards or design values of hydraulic structures if impact of climate change is to be taken into consideration during hydraulic design of water resources works.

Acknowledgements

The authors would like to thank Climate Change Knowledge Network (CDKN) and Global Change SysTem Analysis Research and Training (START) for the financial support to carry out this research. They are also grateful to Dr. Divas B. Basnyat to improve the quality of the paper.

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